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To: Dr. D. Mills
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A LASER TECHNIQUE FOR HYDRIDE STRAIN

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Laser speckle interferometry coupled with computer vision has been used to monitor a previously grown hydride blister as it dissolved on the surface of a heated sample of zirconium pressure tube material. The change of in-plane strain with time was seen, along with a change in the microstructure of the surface at the edge of the blister.

INTRODUCTION

Laser speckle interferometry has been used to observe a hydride blister on a zirconium pressure tube sample of the type used in CANDU reactors. This optical monitoring technique provided full field, non contact observation of surface strain as the blister dissolved at elevated temperature. A vacuum chamber was used to avoid heat waves and to avoid oxidation of the sample, since it was kept at 340 C to permit diffusion of hydrogen from the blister back into solution in the zirconium metal.

Speckle interferometry and holographic interferometry are sensitive techniques for the measurement of strain on the surface of diffusely reflecting objects. While both of these forms of interferometry are of use in the measurement of out-of-plane displacement and strain, speckle interferometry can provide measurement of in-plane displacement and strain when symmetric dual illumination is employed/1/. With this form of illumination, the fringe pattern shows a specific component of in-plane strain.

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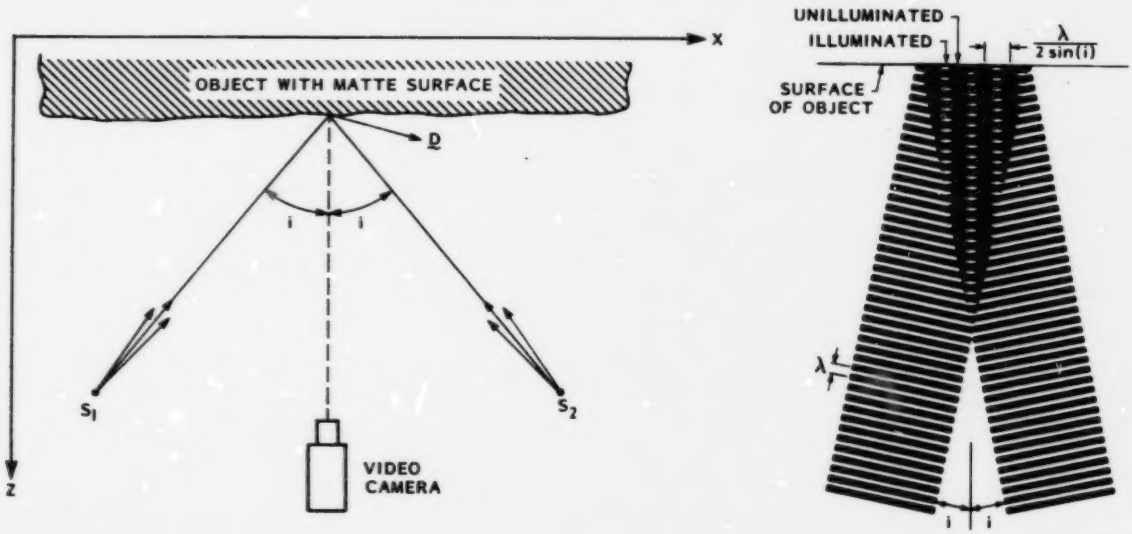
THEORY FOR SPECKLE INTERFEROMETRY

Leendertz/2/ laid down the fundamentals of interferometric measurement with speckle techniques, while Archbold and Ennos/3/ applied the method to observe longitudinal strain in a pipe joint, and a more recent description is given by Vest/4/. Originally, speckle interferometry gave poor quality interferograms of low fringe visibility, or it required off-line handling of film in an optical processor to yield high contrast fringes. Fortunately, video cameras and high speed digital processing give speckle interferometry the ability to provide high visibility fringes in real time as reported on by Tyrer/5/ who describes ESPI (Electronic Speckle Interferometry).

Any diffuse surface illuminated by laser light appears grainy or speckled. This appearance is due to interference, in which the light scattered from the surface microstructure interferes constructively to give a bright speckle or destructively to give a dark speckle. While it is a fact that light from an ordinary light bulb does interfere, it is only with coherent light from a laser that the interference pattern (the speckle) remains stationary so that it can be captured by the eye or a camera. Although it is customary to think of speckle patterns as random, they will in fact remain stationary as long as the apparatus remains stable. The constancy of the speckles seen on an object affords us the opportunity to monitor an object over an extended period of time.



(a) The x-component of movement D is detected.

(b) A set of parallel planes of illumination is set up in front of the object.

Fig 1: DISI - Dual illumination speckle interferometry.

The principle of speckle interferometry for the measurement of in-plane strain is given in Fig 1 (a), where a camera views a diffusely reflecting surface illuminated from each side by light obtained from the same laser. Since the light is coherent, the two beams interfere at the surface of the object in a stationary pattern of closely spaced lines which form a structured illumination pattern indicated in (b). The spacing between the illumination lines depends on the angle of incidence, i, and the wavelength of the light as given in the figure. If the object remains at rest,

moves in the Y direction, or moves in the X direction exactly one or more cycles of the illumination pattern, the camera will see exactly the same image, as long as the motion is smaller than the size of the speckles. The speckle patterns seen in two successive images are said to be correlated when this occurs. Otherwise, the speckle is decorrelated.

Using a computer vision system as indicated in Fig 2, speckled images can be acquired digitally and can be subtracted from each other on a point by point basis. When two correlated images are subtracted the resulting difference image has zero intensity, that is, it is dark. On the other hand, bright regions in the difference image show locations where the speckle pattern has become decorrelated between the two images. This would arise due to displacement wherever a given microscopic patch of the surface has moved from, say, a bright illumination line to a dark line, while a previously un-illuminated patch moves into an illumination maximum. Since the microscopic terrain which is being illuminated is different, the speckle pattern is different, and a bright fringe is seen.

Another cause for speckle decorrelation, which would give a bright fringe in a difference image, is change in the surface microstructure.

Since negative values can occur when image intensities are subtracted, the difference values can be squared or their absolute value can be displayed. The square was taken in this work so that the fringe pattern formula would be similar to that for holographic interferometry.

The fringe pattern intensity, I, may be written as:

$$I=1-V\cos(2\pi OPD/\lambda),$$

where V is fringe visibility, λ is the laser wavelength, and the optical path difference is:

$$OPD=2\sin(i)\, D_x.$$

Here D_x is the component of in-plane surface displacement lying in a plane containing the two illumination beams, which are symmetrically located on each side of the normal at an angle of incidence i, as seen in Fig 1.

APPARATUS

Dual illumination ESPI was done on a heated sample with the apparatus shown in Fig 2. The sample was enclosed in a vacuum chamber with a glass bell jar to reduce heat waves and to avoid oxidation of the sample at elevated temperature. The use of ESPI at very high temperatures was described by Lokberg and Malmo/6/, who used resistance heating to heat samples up to their melting point, without use of a vacuum chamber. They were able to capture surface effects such as oxidation over a monitoring time span of several minutes.

The required vacuum to avoid heat waves due to residual air in the vacuum chamber was estimated as 1.6% of atmospheric. Since the measured pressure was 0.03% of atmospheric, it was concluded that heating and convection of the residual gas in the vacuum chamber should not affect the observed fringe patterns.

The sample was heated by radiant heating from a cone heater as seen in Fig 3. To retain the heat in the sample and to shield the bell jar, a heat shield was provided around the sample. This was an inverted glass beaker with a layer of gold deposited on the inside and with a hole for the illumination beams and for viewing. A further aid to reduction of heat waves was use of a fan to keep the outside surface of the bell jar at room temperature.

The sample shown in Fig 3 incorporated a 4 mm diameter hydride blister that had been previously grown using an impinging air jet on a section of pre-hydrided pressure tube. A portion containing the blister was cut from the original tube and was welded into the sample by electron beam welding.

Thermal design for the sample holder was aimed at stability for long term monitoring. This was to be done without use of separate insulators which could introduce unknown amounts of slippage at points of attachment during temperature cycles. Thus, while the hydride blister part of the sample was to be heated, it was thought necessary to cool the base of the sample so that the apparatus, including the optical table, would not gradually be heated. The concept adopted was to supply the top of the sample with heat, restrict the flow of heat on its way to the base, and to clamp the temperature of the base to room temperature through use of a water cooled heat sink.

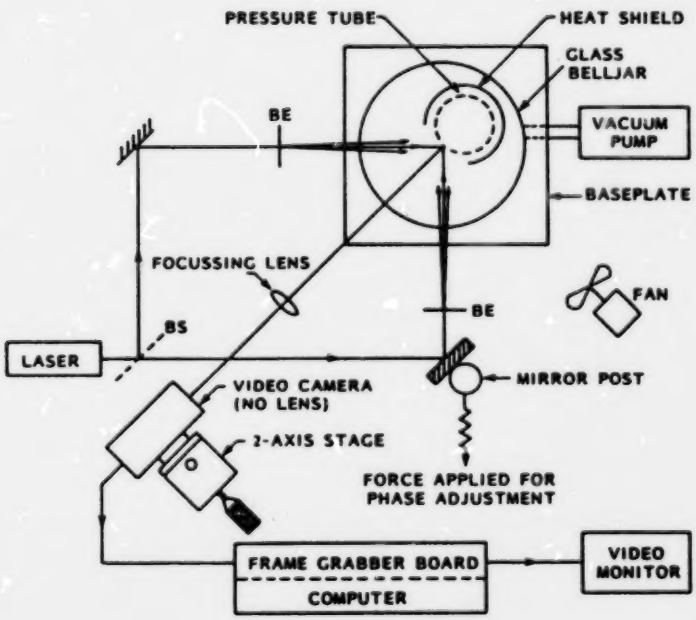


Fig 2: Apparatus

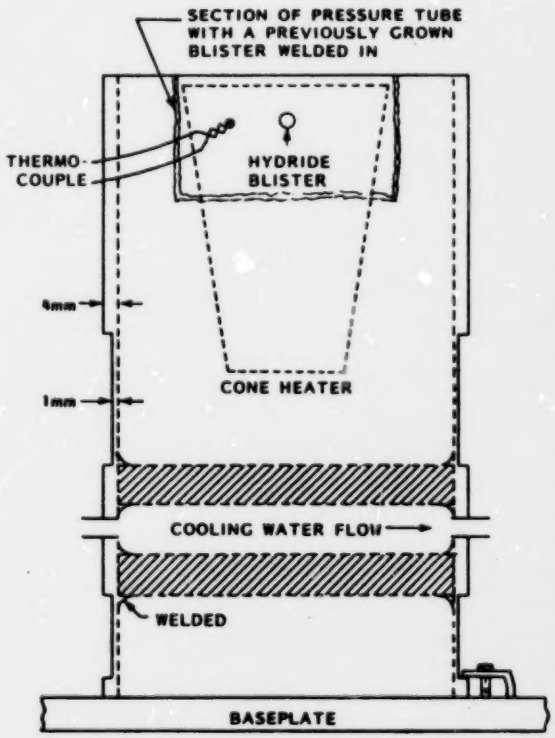


Fig 3: Sample

OBSERVATION OF STRAIN AND BLISTER DISSOLUTION

In Fig 4 the difference display described in the theory section is shown for two images taken 16 hours apart. To accommodate drift, the phase between the two illumination beams, and the camera position, had been adjusted to obtain the best correlation between the two images, by adjusting for the darkest possible difference image in the upper right corner. The main bright regions of decorrelation are seen to be a ring around the blister at its edge where the blister would be expected to dissolve the fastest, and an area inside the blister where strain may be expected to occur. Additional small patches of decorrelation are seen in the region beyond the main blister.

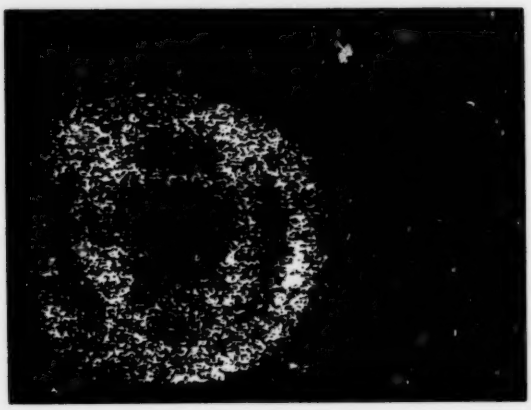


Fig 4: Interferogram obtained after 16 hours of heating.

PHASE REVERSAL TECHNIQUE AND MICROSTRUCTURE CHANGES

A phase reversal test was devised in this work to distinguish between strain and microstructure change as causes for speckle decorrelation. The relative phase of the two illumination beams is changed such that, in the difference image, dark fringes become bright and bright fringes become dark for displacement induced fringes. What has happened is that the pattern of illumination interference lines has moved sideways half a cycle and points on the surface that have moved half a cycle are still illuminated as if they had not moved at all. However, where the surface microstructure has changed the speckle pattern will have changed independently of the phase of the illumination beams so that these regions will always be bright in the difference image.

A normal difference image for 16 hours is shown in Fig 5(a), obtained by adjusting the phase for minimum difference in the upper right corner, while the difference image in (b) was obtained from the same initial image by adjusting the optical phase, while viewing real-time fringes, for maximum brightness in the upper right corner. In comparing (a) and (b), areas which are bright in both images are areas where the surface microstructure has changed. This area of microstucture change is highlighted in (c), which is the difference between the normal and the phase reversed difference images. In (c), areas of large change between (a) and (b) show as bright areas, whereas the areas where phase reversal had no correlated effect show as darker areas. It appears that the microstructure changes the most at the edge of the blister where the blister would be expected to dissolve the fastest.

(a) Normal (b) Phase reversed (c) Difference of (a) and (b)

Fig 5: Phase reversal provides distinction between strain fringes and surface microstructure changes.

A filtered intensity profile taken across the central region of Fig 5 is shown in Fig 6. The intensity is seen to dip in (c) where the microstructure changed at the blister edge. In (a) and (b) the displacement fringes are seen in addition to the microstructure changes.

(a) Normal (b) Reversed (c) Difference

Fig 6: Intensity profiles for phase reversal technique.

To clearly show the utility of the phase reversal technique in discrimination between strain and microstructure change, the above intensity profiles are displayed again vertically in Fig 7. The two broken lines show the microstructure change at the blister edge, while the solid lines show that the intensity changes from peak to valley and valley to peak in the strain fringes arcross the blister.

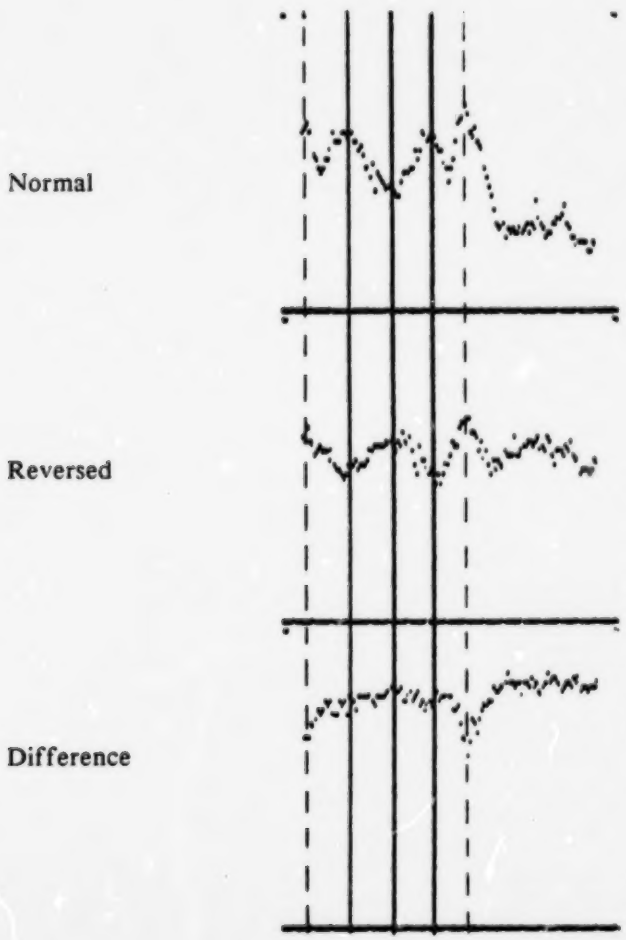
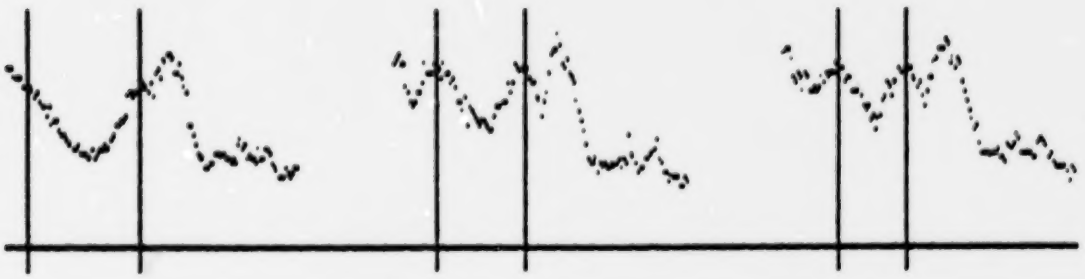


Fig 7: Phase reversal technique analysis.

EVOLUTION OF BLISTER STRAIN WITH TIME

The blister was kept at 340 C throughout the course of the experiment so that its temperature was high enough to permit hydrogen migration from the blister back into solid solution in the surrounding zirconium metal. Fringe patterns were obtained which showed the changes which occurred for three time intervals of 8, 16, and 24 hours, respectively. The corresponding intensity profiles are shown in Fig 8, where vertical lines show the peaks in the strain fringe patterns.



(a) 8 hours (b) 16 hours (c) 24 hours

Fig 8: Intensity profiles show change of strain with time.

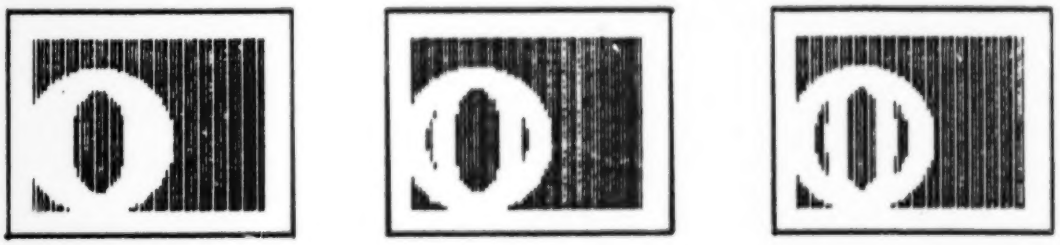
From the separations of these peaks and an angle of incidence i=45 degrees, one may infer the following strain values:

(a)	8 hours	110 microstrains
(b)	16	130
(c)	24	170

These values are extracted on the assumption of uniform strain across the blister.

CALCULATED FRINGE PATTERNS FOR STRAIN

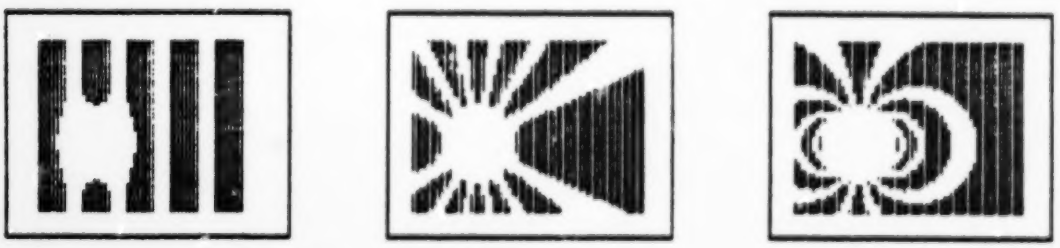
A computer simulation using an adaptation of a program for holographic interferometry/7/ was done for fringe patterns using the intensity formula given in the theory section for strain and using a Gaussian (arbitrarily chosen) for microstructure decorrelation at the blister edge. A printer plot of simulated fringe patterns is given in Fig 9 for the strain values found from Fig 8. Fig 9(b) may be compared with Fig 4. Strain was taken as zero beyond the centreline of the dissolution ring and was taken as constant when well within the ring. In the transition region from the central region to the ring centreline, the strain was taken as increasing, leading to patterns in Fig 9 which were seen to agree qualitatively with the data. Other models for the strain as a function of distance from the centre of the blister could be tested in a similar fashion.



(a) Strain=0.00011 (b) 0.00013 (c) 0.00017

Fig 9: Calculated fringe patterns for strain across hydride blister.

A simulation of fringe patterns which could perhaps be expected to develop after one or two weeks of blister dissolution is given in Fig 10, which shows the effect of different assumed strain models. The blister itself is shown completely white in the figure to indicate that microstructure changes could be expected to occur over the entire blister after an extended period of time. A lesser magnification for the camera is assumed than in the previous figure so that strain fringes can be seen all around the blister.



(a) Uniform strain (b) $1/r$ (c) $1/r^2$

Fig 10: The fringe pattern on the metal surrounding the blister could give definitive validation of the correct strain model.

To obtain an experimental fringe pattern such as one of those in Fig 10 would require automatic control to compensate for drift of the phase between the two illumination beams and drift of the camera position. The control system would maintain speckle correlation in some reference position in the fringe pattern.

CONCLUSIONS

Laser speckle interferometry coupled with computer vision has been used to monitor a hydride blister as it evolved on the surface of a sample of zirconium pressure tube material heated to 340 C. This technique provided full field, non contact observation of surface strain as the blister dissolved at elevated temperature. A vacuum chamber was used to avoid heat waves and to avoid oxidation of the sample. The change of in-plane strain with time was seen, along with surface microstructure change at the edge of the blister as it dissolved.

Controls were provided for adjustment of camera position and illumination phase. With manual operation, fringe patterns were obtained for monitoring periods up to 24 hours. With automation, longer monitoring intervals should be achievable so that strain patterns in the zirconium metal around the blister could be observed if they develop during dissolution.

Thanks go to M. Leger for the idea of dissolving a previously grown hydride blister rather than taking the time to grow one and to O. Kiir for supplying a sample.

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